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Original Article

OPTIMIZATION OF PROCESS PARAMETERS ON THRUST FORCE AND DELAMINATION FACTOR IN DRILLING OF CARBON FIBER REINFORCED COMPOSITES

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ABSTRACT

The major objective of this work was to investigate a statistical model, based on Taguchi technique and to estimate the quality of drill in CFRP composite material prepared by hand layup technique. The design of experiments were made to investigate the influence of drill parameters such as cutting speed, feed rate and drill diameter on thrust force and delamination factor in drilling of CFRP laminates. Analysis of variance (ANOVA) was used to analyze the significance level of every drill parameters. The statistical model yields the results showing that the speed and feed rate were the major parameters affecting significantly the drilling process. Delamination due to drilling was analyzed by the stereomicroscope.

KEYWORDS: CFRP (Carbon Fiber Reinforced Polymer), Drilling, Taguchi, ANOVA, Delamination, Thrust Force & Optimization

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INTRODUCTION

CFRPs are finding a vast exposure in the field of important applications, as they possess unique properties like low weight, high strengths, excellent fatigue, corrosion resistance etc. CFRP materials can be used widely in the aeronautical and automobile industries as they possess light weight property, which helps in the reduction in fuel consumption and behaves environmental friendly. Fastening is the major issue, as it involves machining (drilling) of composites, which is a difficult process in the industrial applications. Drilling of CFRP is very much challenging due to the anisotropic and non-homogenous nature (1).

Assessment of drilling performance significantly depends on the quality of hole, which is the major parameter, as it highly influences the performance of the assemblies (2). Researchers (3-5) are still developing different methods for the assessment of drilled hole quality based on cracks, damage, internal cracks and errors in dimensions. It is shown from the survey that there is a significant relation between delamination and thrust force, and that the continuous monitoring of force during drilling process helps in providing reliable information of delamination. This work concentrates on the optimization of process parameters on drilling performance of CFRP composites.

MATERIAL AND METHODS

Material

Plain woven carbon fiber of density of 250 g-m^2 by Vortorex-India was used as reinforcement. Epoxy (Araldite-LY556) resin and hardener (Amine based – HY951) supplied by Ciba-Geigy was used with resin: hardener – 100: 10.

Preparation of Test Specimen

The laminates were fabricated using hand layup technique with seven layers (each 0.5mm thick) of fibers used to generate a laminate of 3.5mm thickness. Stacking was maintained with 0^0 /90^0 orientation and the volume fraction was 0.65. Post curing was carried out at 90^0 C.; totally the laminates were fabricated to the dimensions of 25mmX10mmX3.5mm.

Experimental Method

A Sensitive drilling machine (Machine type: Sensitive drilling machine Current: 16 amp, Voltage: 415V, 3 Ph, 50 Hz) is used for the drilling of the CFRP composite. A Drill tool dynamometer (Type: Two- component dynamometer, Max thrust force: 500 kgF, Max torque: 20 kgm**)** was used for the determination of thrust force while drilling the CFRP composite. Drilling was performed using a sensitive drilling machine with a varying feed rate (0.104, 0.211 & 0.315 mm/rev) and cutting speed (1260, 1860, & 2700 rpm). Thrust force as per the research carried out, is the major factor for delamination. Efficiency can be increased for a machine if the critical thrust force is known.

DOE was done using Taguchi method with an orthogonal array of L27 for analyzing the effect of process parameters such as diameter, cutting speed and feed rate on the responses such as thrust force and delamination factor.

Delamination damage can be assessed by calculating the delamination factor which is given by the ratio of maximum diameter (D_{max}) and nominal diameter (D_{nom}). Using a stereo microscope with view 7 software, images were captured with the help of pixel based technique to find D_{max} & D_{nom} (F_d=D_{max}/D_{nom}).

Design of Experiments

For the formulation of design of experiments taguchi method was used, as it is the easiest method to adopt with minimum knowledge of statistics and requires minimum number of experiments to be conducted. For this work, cutting speed, feed rate and drill tool diameter are considered as the cutting parameters and the output of these parameters is the quality of drill hole (delamination factor).

Taguchi analysis is done using MINITAB 17 software.

Table 1: Levels and Factors Considered for Analysis

Levels	Diameter (mm)	Cutting Speed (rpm)	Feed Rate (mm/rev)
1	2	1260	0.104
2	3	1860	0.211
3	4	2700	0.315

RESULTS AND DISCUSSIONS

Effect of Drill Tool Diameter, Spindle Speed and Feed Rate on Thrust Force

The drill tool dynamometer was used to measure the thrust force exerted by the drill tool during the drilling.

Table 2: Thrust Force measured using Drill Tool Dynamometer

Experiment no	Diameter (mm)	Feed Rate (mm/rev)	Cutting Speed (rpm)	Thrust Force (kgf)
1	2	0.104	1260	58.86
2	2	0.211	1260	78.48
3	2	0.315	1260	176.58
4	2	0.104	1860	49.05
5	2	0.211	1860	68.67
6	2	0.315	1860	88.29
7	2	0.104	2700	49.05
8	2	0.211	2700	29.43
9	2	0.315	2700	39.24
10	3	0.104	1260	98.1
11	3	0.211	1260	137.34
12	3	0.315	1260	206.01
13	3	0.104	1860	88.29
14	3	0.211	1860	117.72
15	3	0.315	1860	137.34
16	3	0.104	2700	58.86
17	3	0.211	2700	49.05
18	3	0.315	2700	117.72
19	4	0.104	1260	88.29
20	4	0.211	1260	137.34
21	4	0.315	1260	156.96
22	4	0.104	1860	117.72
23	4	0.211	1860	127.53
24	4	0.315	1860	156.96
25	4	0.104	2700	88.29
26	4	0.211	2700	117.72
27	4	0.315	2700	156.96

Depending on the values obtained and tabulated in Table 2, a main effect plot for thrust force was generated as shown in figure 1. The study of the plot reveals that, the thrust force increases significantly with the increase in drill tool diameter and feed rate, whereas, it decreases with the increase in cutting speed. The increase in thrust force may be attributed to the rubbing action between tool surface and chip, which is created due to increased thickness of chip as well as reduced clearance with drill surface.

An optimization plot of mean thrust force for process parameters such as diameter, feed rate and cutting speed is actualized as shown in figure 2. The plot reveals that the minimum thrust force of 13.9157 N was obtained for the following drilling process parameters: i. diameter = 2mm, ii. Feed rate = 0.315 mm/rev, iii. Cutting speed = 1860 rpm. The combination of these process parameters provides least thrust force on the work piece which also reduces the damages like delamination and fiber pull out induced while performing the drill operation.

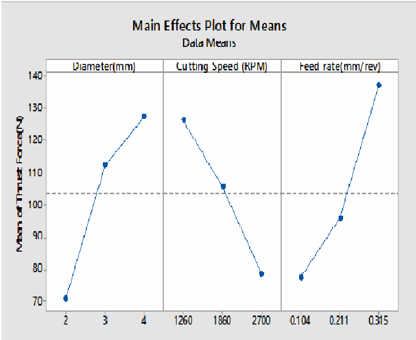

Figure 1: Main Effect Plot for Thrust Force

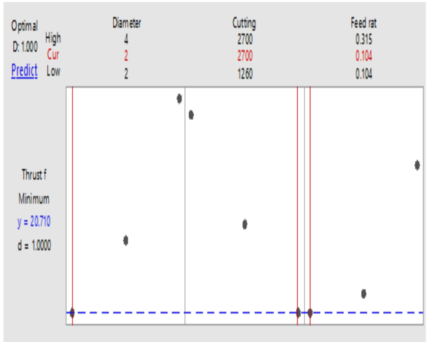

Figure 2: Optimization Plot for Mean Thrust Force

Effect of Drill Tool Diameter, Spindle Speed and Feed Rate on Delamination Factor

Measurement of delamination factor was done using stereomicroscope attached to PC, which has view7 software installed. In view7, software measurement of Dmax was done using 3-point circle covering the delamination damage around the hole, and measurement of Dnom was done by taking the average of 4 diameters at 0°, 45°, 90° and 135°.

Table 3: Measured Values of Delamination Factor using View 7 Software

Experiment No	Diameter (mm)	Feed Rate (mm/rev)	Cutting Speed (rpm)	D_{max}(mm)	D_{nom}(mm)	Delamination factor
1	1260	0.104	1260	2.34	2.025	1.155556
2	1260	0.211	1260	2.42	2.0425	1.184823
3	1260	0.315	1260	2.54	2.105	1.206651
4	1860	0.104	1860	2.46	2.0575	1.195626
5	1860	0.211	1860	2.54	2.1025	1.208086
6	1860	0.315	1860	2.6	2.145	1.212121
7	2700	0.104	2700	2.46	2.0425	1.204406
8	2700	0.211	2700	2.38	2.0125	1.182609
9	2700	0.315	2700	2.36	2.04	1.156863
10	1260	0.104	1260	3.56	3.0075	1.183707
11	1260	0.211	1260	3.72	3.0475	1.220673
12	1260	0.315	1260	3.62	3.14	1.152866
13	1860	0.104	1860	3.94	3.185	1.237049
14	1860	0.211	1860	4.38	3.0175	1.451533
15	1860	0.315	1860	3.7	3.025	1.22314
16	2700	0.104	2700	3.48	3.0325	1.147568
17	2700	0.211	2700	3.4	3.035	1.120264
18	2700	0.315	2700	3.7	3.0375	1.218107
19	1260	0.104	1260	5.46	4.105	1.330085
20	1260	0.211	1260	6.12	4.1575	1.472038
21	1260	0.315	1260	5.8	4.1175	1.408622
22	1860	0.104	1860	4.84	4.095	1.181929
23	1860	0.211	1860	6.04	4.0325	1.49783
24	1860	0.315	1860	5.9	4.2025	1.403926
25	2700	0.104	2700	5.08	4.0625	1.250462
26	2700	0.211	2700	6.16	4.1875	1.471045
27	2700	0.315	2700	5.5	4.0975	1.342282

Using the values tabulated in Table 3, a main effect plot for delamination factor was produced (figure 3). The effect of diameter, feed rate and cutting speed on the delamination factor was studied using the plot. According to the graph, there was an increase in delamination with the increase of diameter and feed rate and a decrease in delamination with increase in

cutting speed. As the feed rate increases thrust force increases which is applied to the uncut plies exceeding the inter-ply bonding strength and causing smaller chips and delamination. The effect of spindle speed is insignificant as the rate of increase in thrust force and delamination with respect to increase in spindle speed is in decreasing trend.

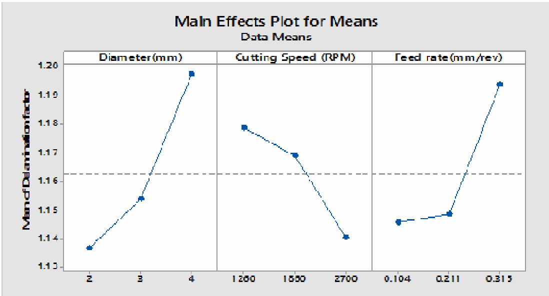

Figure 3: Main Effect Plot for Delamination Factor

Minimum delamination factor (DF) 1.0718 was obtained for 2mm diameter, 2700 rpm and 0.104 mm/rev at entry of the drilled hole and DF of 1.451533 was obtained at exit.

Contour Plots for Correlating the Affect of Parameters and Responses

Contour plots were drawn to correlate the effects of parameters (feed rate, spindle speed and drill dia) on the responses (thrust force and delamination factor) and the results were summarized to obtain the minimum and maximum values of the responses with respect to the cutting parameters.

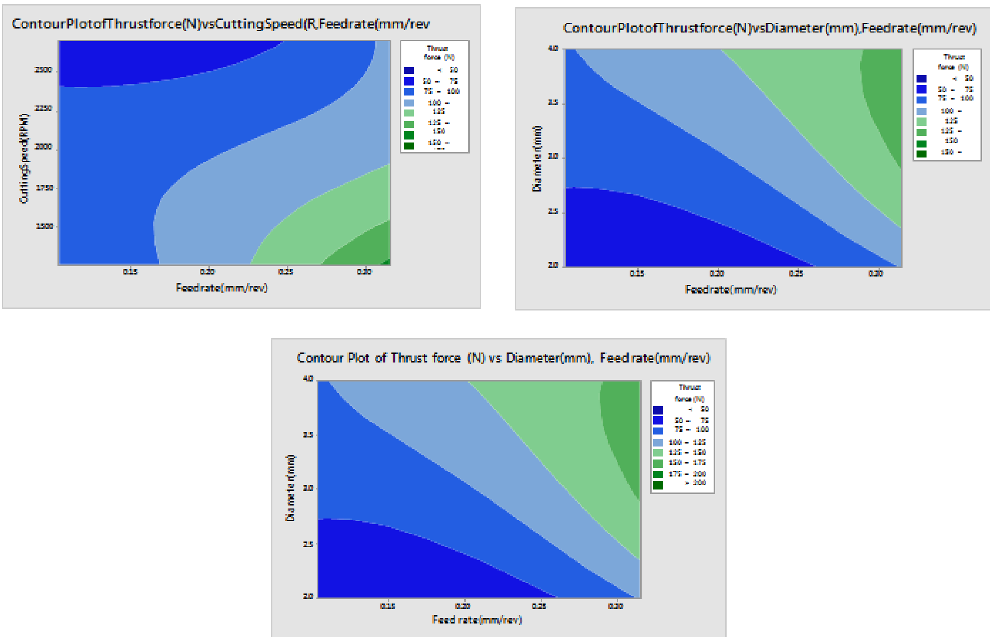

Figure 4: Contour Plots for Thrust Force (N) vs Cutting Speed (rpm), Feed Rate (mm/rev) & Diameter (mm)

It can be noted in the above graph, thrust force was minimum for the feed rate between 0.15mm/rev to 0.25mm/rev and the cutting speed between the 1750rpm to 2500rpm. The trust force was minimum in the range 0.1mm/rev to 0.25mm/rev feed rate and 2mm to 2.75mm diameter, and the trust force was minimum for the range of 1200rpm to 1750rpm cutting speed and 3mm to 4mmdiameter.

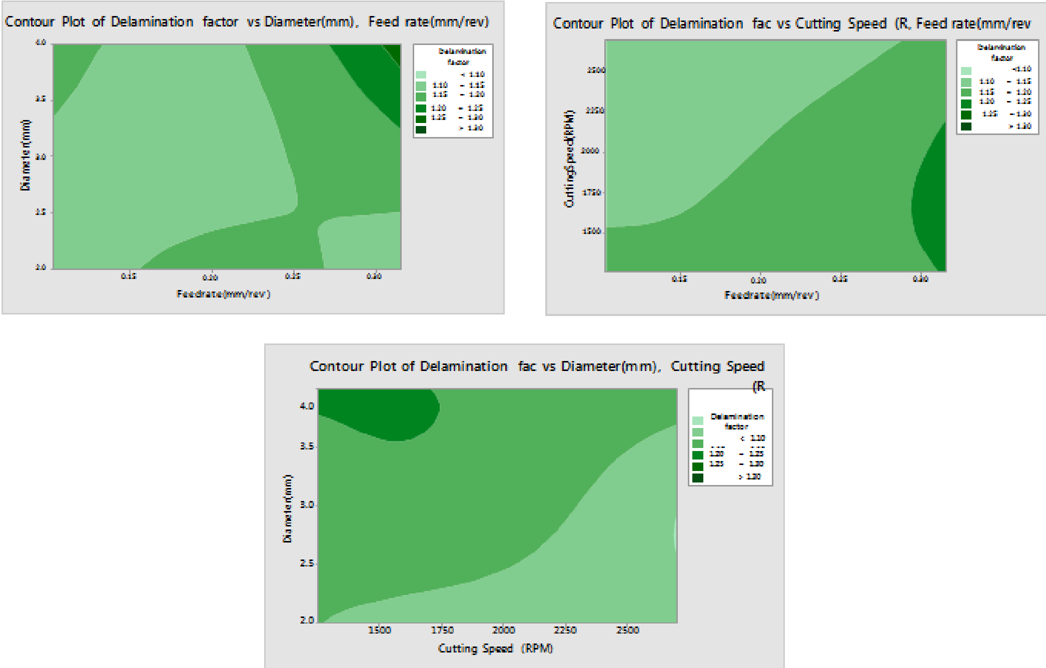

Figure 5: Contour Plots for Delamination Factor vs Cutting Speed (rpm), Feed Rate (mm/rev) & Diameter (mm)

The above graph shows, minimum delamination error was obtained for the range of 0.15mm/rev to 0.25mm/rev and 2000rpm to 2500rpm. The minimum delamination was found in the range 0.1mm/rev to 0.20mm/rev feed rate and 2.5mm to 3.5mm diameter. The delamination factor was minimum for the range 1200rpm to 2700rpm and 2.5mm to 3.5mmdiameter.

ASSESSMENT OF HOLE QUALITY USING STEREO MICROSCOPE

Stereomicroscope for capturing images of the drilled hole were taken using stereomicroscope and calibrated for measuring average diameter using 4 diameters and maximum diameter using pixel based technique on view7software.

Figure 6 shows images of the drilled hole of 2mm diameter with different feed rates and cutting speeds

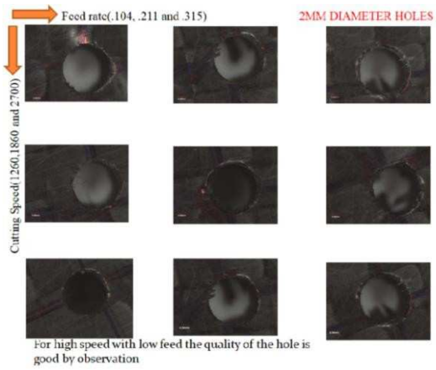

Figure 6: Drilled Hole Images for 2mm Diameter
(a-Feed rate: 0.104mm/rev and 1260rpm**)(b-**Feed rate: 0.211mm/rev and 1260rpm**)**
(c-Feed rate: 0.315mm/rev and 1260rpm**)(d-**Feed rate: 0.104mm/rev and 1860rpm**)**
(e-Feed rate: 0.211mm/rev and 1860rpm**)(f-**Feed rate: 0.315mm/rev and 1860rpm**)**
(g-Feed rate: 0.104mm/rev and 2700rpm**)(h-**Feed rate: 0.211mm/rev and 2700rpm**)**
(i-Feed rate: 0.315mm/rev and 2700rpm**)**

Figure 6(c) shows the image of the drilled hole, which has maximum delamination factor and figure 6(g) shows the image of the drilled hole, which has least delamination factor. By observation of the images from figure 6(g), hole with drilling parameters of feed rate 0.104mm/rev and cutting speed 2700rpm is found to be of good quality.

Figure 7 shows images of the drilled hole of 3mm diameter with different feed rates and cutting speeds

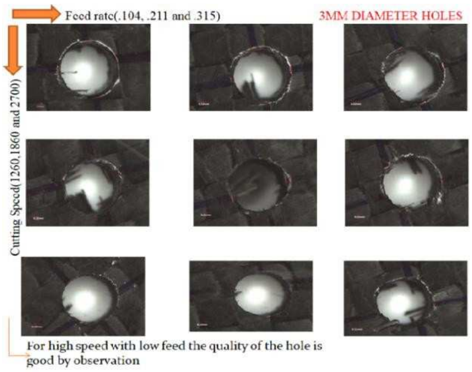

Figure 7: Drilled Hole Images for 3mm Diameter

(**a**-Feed rate: 0.104mm/rev and 1260rpm) (**b**-Feed rate: 0.211mm/rev and 1260rpm)
(**c**-Feed rate: 0.315mm/rev and 1260rpm) (**d**-Feed rate: 0.104mm/rev and 1860rpm)
(**e**-Feed rate: 0.211mm/rev and 1860rpm) (**f**-Feed rate: 0.315mm/rev and 1860rpm)
(**g**-Feed rate: 0.104mm/rev and 2700rpm) (**h**-Feed rate: 0.211mm/rev and 2700rpm)
(**i**-Feed rate: 0.315mm/rev and 2700rpm)

Figure 7(c) shows the image of the drilled hole which has maximum delamination factor, and figure 7(g) shows the image of the drilled hole, which has least delamination factor. By observation of the images from figure 7(g), hole with drilling parameters of feed rate 0.104mm/rev and cutting speed 2700rpm is found to be of good quality.

Figure 8 shows images of the drilled hole of 3mm diameter with different feed rates and cutting speeds.

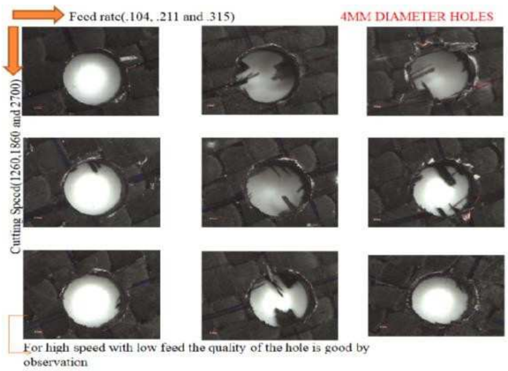

Figure 8: Drilled Hole Images for 4mm Diameter

(**a**-Feed rate: 0.104mm/rev and 1260rpm) (**b**-Feed rate: 0.211mm/rev and 1260rpm)
(**c**-Feed rate: 0.315mm/rev and 1260rpm) (**d**-Feed rate: 0.104mm/rev and 1860rpm)
(**e**-Feed rate: 0.211mm/rev and 1860rpm) (**f**-Feed rate: 0.315mm/rev and 1860rpm)
(**g**-Feed rate: 0.104mm/rev and 2700rpm) (**h**-Feed rate: 0.211mm/rev and 2700rpm)
(**i**-Feed rate: 0.315mm/rev and 2700rpm)

Figure 8(c) shows the image of the drilled hole, which has maximum delamination factor and figure 8(g) shows the image of the drilled hole, which has least delamination factor. By observation of the images from figure 8(g), hole with drilling parameters of feed rate 0.104mm/rev and cutting speed 2700rpm is found to be of good quality.

CONCLUSIONS

In the current work, considering the importance of CFRP in the field of material and market, an idea was undertaken to optimize the process parameters and to investigate the quality (delamination factor) of drilled hole. The conclusions are drawn from the experimental study as follows.

- Drilled hole of 2mm diameter with cutting parameters of 0.315mm/rev feed rate and 1860rpm cutting speed has least thrust force of13.4197N.
- Drilled hole of 2mm diameter with cutting parameters of 0.104mm/rev feed rate and 2700rpm cutting speed has least delamination factor was 1.07185 at entry and 1.451533 at exit.

By the results, it is evident that the feed rate is the factor that makes larger contribution to thrust force and delamination. It is viewed that there is a co-relation between thrust force and delamination. Furthermore, the work reveals that there is no significant value of spindle speed on the responses. Lower feed rates have to be used for higher spindle speeds to reduce the delamination damage.

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